Forest Carbon Assessment for the George Washington and Jefferson National Forests in the Forest Service's Southern Region

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1.0 Introduction

Carbon uptake and storage are some of the many ecosystem services provided by forests and grasslands. Through the process of photosynthesis, growing plants remove carbon dioxide (CO_2) from the atmosphere and store it in forest biomass (plant stems, branches, foliage, roots) and much of this organic material is eventually stored in forest soils. This uptake and storage of carbon from the atmosphere helps modulate greenhouse gas (GHG) concentrations in the atmosphere. Estimates of net annual storage of carbon indicate that forests in the United States (U.S.) constitute an important carbon sink, removing more carbon from the atmosphere than they are emitting (Pan *et al.*, 2011b). Forests in the U.S. remove the equivalent of about 12 percent of annual U.S. fossil fuel emissions or about 206 teragrams of carbon after accounting for natural emissions, such as wildfire and decomposition (US EPA, 2015; Hayes *et al.*, 2018).

The Intergovernmental Panel on Climate Change (IPCC) has summarized the contributions of global human activity sectors to climate change in its Fifth Assessment Report (IPCC, 2014). From 2000 to 2009, forestry and other land uses contributed just 12 percent of human-caused global CO_2 emissions.[1] The forestry sector contribution to GHG emissions has declined over the last decade (FAOSTAT, 2013; IPCC, 2014; Smith *et al.*, 2014). Globally, the largest source of GHG emissions in the forestry sector is deforestation,(Pan *et al.*, 2011b; Houghton *et al.*, 2012; IPCC, 2014) defined as the removal of all trees to convert forested land to other land uses that either do not support trees or allow trees to regrow for an indefinite period (IPCC, 2000). However, the United States is experiencing a net increase in forestland in recent decades because of the reversion of agricultural lands back to forest and regrowth of cut forests (Birdsey *et al.*, 2006), a trend expected to continue for at least another decade (Wear *et al.*, 2013; USDA Forest Service, 2016).

Forests are dynamic systems that naturally undergo fluctuations in carbon storage and emissions as forests establish and grow, die with age or disturbances, and re-establish and regrow. When trees and other vegetation die, either through natural aging and competition processes or disturbance events (e.g., fires, insects), carbon is transferred from living carbon pools to dead pools, which also release carbon dioxide through decomposition or combustion (fires). Management activities include timber harvests, thinning, and fuel reduction treatments that remove carbon from the forest and transfer a portion to wood products. Carbon can then be stored in commodities (e.g., paper, lumber) for a variable duration ranging from days to many decades or even centuries. In the absence of commercial thinnings, harvests, and fuel reduction

[1] Fluxes from forestry and other land use (FOLU) activities are dominated by CO_2 emissions. Non-CO_2 greenhouse gas emissions from FOLU are small and mostly due to peat degradation releasing methane and were not included in this estimate.

treatments, forests will thin naturally from mortality-inducing disturbances or aging, resulting in dead trees decaying and emitting carbon to the atmosphere.

Following natural disturbances or harvests, forests regrow, resulting in the uptake and storage of carbon from the atmosphere. Over the long term, forests regrow and often accumulate the same amount of carbon that was emitted from disturbance or mortality (McKinley *et al.*, 2011). Although disturbances, forest aging, and management are often the primary drivers of forest carbon dynamics in some ecosystems, environmental factors such as atmospheric CO_2 concentrations, climatic variability, and the availability of limiting forest nutrients, such as nitrogen, can also influence forest growth and carbon dynamics (Caspersen *et al.*, 2000; Pan *et al.*, 2009).

Box 1. Description of the primary forest carbon models used to conduct this carbon assessment

Carbon Calculation Tool (CCT)

Estimates annual carbon stocks and stock change from 1990 to 2013 by summarizing data from two or more Forest Inventory and Analysis (FIA) survey years. CCT relies on allometric models to convert tree measurements to biomass and carbon.

Forest Carbon Management Framework (ForCaMF)

Integrates FIA data, Landsat-derived maps of disturbance type and severity, and an empirical forest dynamics model, the Forest Vegetation Simulator, to assess the relative impacts of disturbances (harvests, insects, fire, abiotic, disease). ForCaMF estimates how much more carbon (non-soil) would be on each national forest if disturbances from 1990 to 2011 had not occurred.

Integrated Terrestrial Ecosystem Carbon (InTEC) model

A process-based model that integrates FIA data, Landsat-derived disturbance maps, as well as measurements of climate variables, nitrogen deposition, and atmospheric CO_2. InTEC estimates the relative effects of aging, disturbance, regrowth, and other factors including climate, CO_2 fertilization, and nitrogen deposition on carbon accumulation from 1950 to 2011. Carbon stock and stock change estimates reported by InTEC are likely to differ from those reported by CCT because of the different data inputs and modeling processes.

In this section, we provide an assessment of the amount of carbon stored on the George Washington and Jefferson National Forests (NF'S) and how disturbances, management, and environmental factors have influenced carbon storage overtime. This assessment primarily used two recent U.S. Forest Service reports: the Baseline Report (USDA Forest Service, 2015) and Disturbance Report (Birdsey *et al.,* In press). Both reports relied on Forest Inventory and Analysis (FIA) and several validated, data-driven modeling tools to provide nationally consistent evaluations of forest carbon trends across the National Forest System (NFS). The Baseline Report applies the Carbon Calculation Tool (CCT) (Smith *et al.*, 2007), which summarizes available FIA data across multiple survey years to estimate forest carbon stocks and changes in stocks at the scale of the national forest from 1990 to 2013. The Baseline Report also provides information on carbon storage in harvested wood products (HWP) for each Forest Service region. The Disturbance Report provides a national forest-scale evaluation of the influences of disturbances and management activities, using the Forest Carbon Management Framework (ForCaMF) (Healey *et al.*, 2014; Raymond *et al.*, 2015; Healey *et al.*, 2016). This report also contains estimates of the long-term relative effects of disturbance and non-disturbance factors on carbon stock change and accumulation, using the Integrated Terrestrial Ecosystem Carbon (InTEC) model (Chen *et al.*, 2000; Zhang *et al.*, 2012). See Box 1 for descriptions of the carbon models used for these analyses. Additional reports, including the most recent Resource Planning Act (RPA) assessment (USDA Forest Service, 2016) and regional climate vulnerability assessments (McNulty *et al.*, 2015) are used to help infer future forest carbon dynamics. Collectively, these reports incorporate advances in data and analytical methods, representing the best available science to provide comprehensive assessments of NF'SS carbon trends.

1.1 Background

The George Washington and Jefferson NF's, located in the Southern Appalachian Mountains of Virginia, West Virginia and Kentucky, covers approximately 775,120 ha of forestland. Oak / hickory and oak / pine forest types are the most abundant across the George Washington and Jefferson NF's, according to FIA data. The carbon legacy of the George Washington and Jefferson NF's and other national forests in the region is tied to the history of Euro-American settlement, land management, and disturbances. Exploration of the Southern Region by Europeans began in the mid-17th century. In the late 18th century, after the Revolutionary War, settlers cleared forests for mixed agriculture and grazing, establishing farming communities with schools, stores, and mills. Many of these farms, and sometimes entire communities, were abandoned in the mid to late 19th century, as farming technology changed and people moved west or to cities for better economic opportunities. Large logging companies bought up the abandoned farmland and woodlots, constructing logging railroads and camps and stripping much of the timber from the mountains. The lands known today as the George Washington and Jefferson National Forests could hardly have been called a "forest" in the early 1900's. Repeated wildfires, clearing of steep mountain land for farming and grazing, iron ore mining, and widespread, indiscriminate logging led to severe erosion and

Box 2. Carbon Units. The following table provides a crosswalk among various metric measurements units used in the assessment of carbon stocks and emissions.

Tonnes				Grams		
Multiple	Name	Symbol		Multiple	Name	Symbol
				10^0	Gram	G
				10^3	kilogram	Kg
10^0	tonne	t		10^6	Megagram	Mg
10^3	kilotonne	Kt		10^9	Gigagram	Gg
10^6	Megatonne	Mt		10^{12}	Teragram	Tg
10^9	Gigatonne	Gt		10^{15}	Petagram	Pg
10^{12}	Teratonne	Tt		10^{18}	Exagrame	Eg
10^{15}	Petatonne	Pt		10^{21}	Zettagram	Zg
10^{18}	Exatonne	Et		10^{24}	yottagram	Yg

1 hectare (ha) = 0.01 km^2 = 2.471 acres = 0.00386 mi^2
1 Mg carbon = 1 tonne carbon = 1.1023 short tons (U.S.) carbon
1 General Sherman Sequoia tree = 1,200 Mg (tonnes) carbon
1 Mg carbon mass = 1 tonne carbon mass = 3.67 tonnes CO_2 mass
A typical passenger vehicle emits about 4.6 tonnes CO_2 a year

increased flooding. As a result, by the early 1900's, much of the higher elevation mountains and ridges in southwestern Virginia had been transformed into charred stumps and brush fields. In 1911, Congress authorized and directed the Secretary of Agriculture "to examine, locate, and purchase such forested, cut-over, or denuded lands within the watersheds of navigable streams as in his judgment may be necessary to the regulation of the flow of navigable streams or for the production of timber," through the Weeks Law. In 1918, as a result of this Act, the George Washington National Forest (known at the time as the Shenandoah National Forest) was established from these "lands nobody wanted." Subsequently, the Jefferson National Forest was established in 1936. This legacy of timber harvesting and early efforts to restore the forest is visible today, influencing forest age structures, tree composition, and carbon dynamics (Birdsey *et al.*, 2006).

2.0 Baseline Carbon Stocks and Flux

2.1 Forest Carbon Stocks and Stock Change

According to results of the Baseline Report (USDA Forest Service, 2015), carbon stocks in the George Washington NF increased from 58±6.0 teragrams of carbon (Tg C) in 1990 to 70±9 Tg C in 2013, a 20 percent increase in carbon stocks over this period (Fig. 1A). Carbon stocks in the Jefferson NF increased from 37±5.0 teragrams of carbon (Tg C) in 1990 to 54±8 Tg C in 2013, a 46 percent increase in carbon stocks over this period (Fig. 1B).For context, 70.7 Tg C is equivalent to the emissions from approximately 56 million (George Washington) or 43 million (Jefferson) passenger vehicles in a year. Despite some uncertainty in annual carbon stock estimates, reflected by the 95 percent confidence intervals, there is a high degree of certainty that carbon stocks on the George Washington and Jefferson NF's has increased from 1990 to 2013 (Fig. 1).

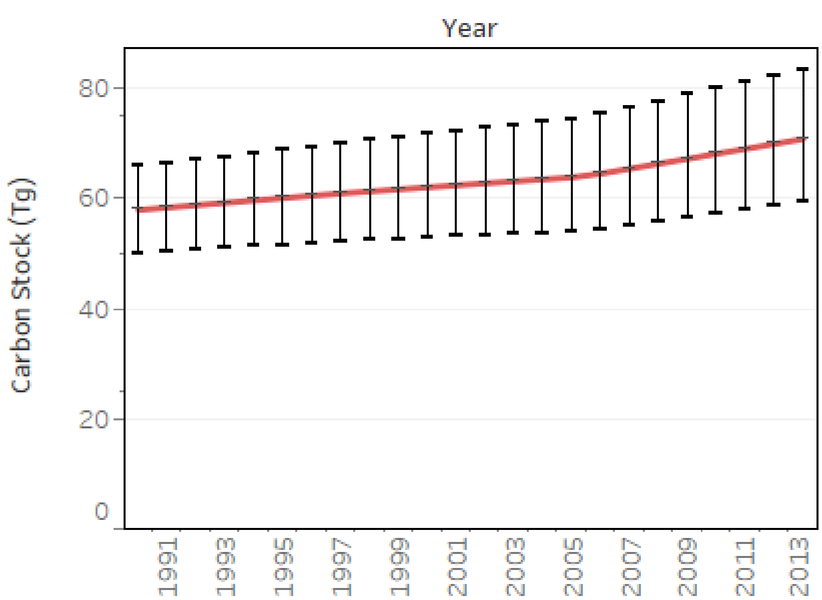


Figure 1a. *Total forest carbon stocks (Tg) from 1990 to 2013 for George Washington National Forest, bounded by 95 percent confidence intervals. Estimated using the CCT model.*

About 33 percent and 32 of forest carbon stocks respectively in the George Washington and Jefferson NF's are stored in the soil carbon contained in organic material to a depth of one meter (excluding roots). The aboveground portion of live trees, which includes all live woody vegetation at least one inch in diameter (Fig. 2) is the largest carbon pool, storing another 44 percent and 47 percent (respectively to the George Washington and Jefferson) of the forest carbon stocks. Recently, new methods for measuring soil carbon have found that the amount of carbon stored in soils generally exceeds the estimates derived from using the methods of the CCT model by roughly 12 percent across forests in the United States (Domke *et al.*, 2017).

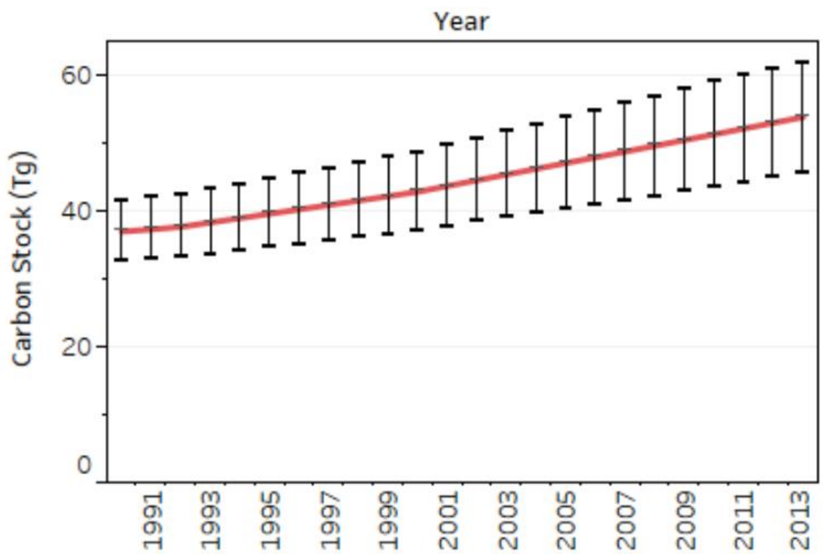


Figure 1b. *Total forest carbon stocks (Tg) from 1990 to 2013 for Jefferson National Forest, bounded by 95 percent confidence intervals. Estimated using the CCT model.*

The annual carbon stock change can be used to evaluate whether a forest is a carbon sink or source in a given year. Carbon stock change is typically reported from the perspective of the atmosphere. A negative value indicates a carbon sink: the forest is absorbing more carbon from the atmosphere (through growth) than it emits (via decomposition, removal, and combustion). A positive value indicates a source: the forest is emitting more carbon than it takes up.

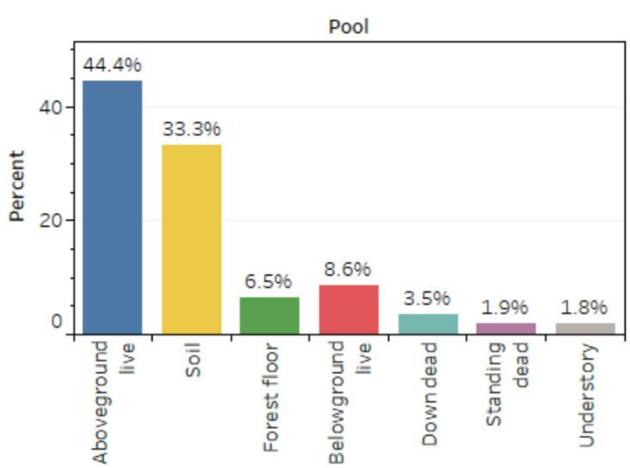


Figure 2a. *Percentage of carbon stocks in 2013 in each of the forest carbon pools, for the George Washington National Forest. Estimated using the CCT model.*

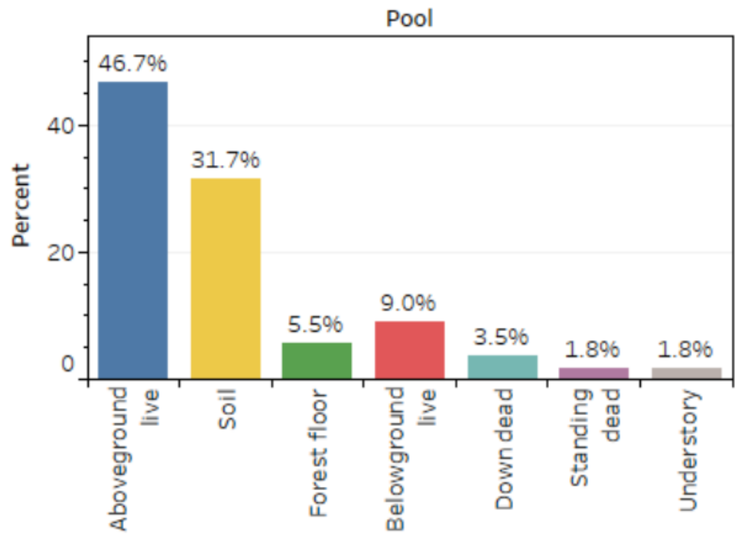


Figure 2b. *Percentage of carbon stocks in 2013 in each of the forest carbon pools, for the Jefferson National Forest. Estimated using the CCT model.*

Annual carbon stock changes in the George Washington NF was -0.95 ± 1.02 Tg C per year (gain) in 1990 and -0.55 ± 1.25 Tg C per year in 2012 (gain) (Fig. 3a). Annual carbon stock changes in the Jefferson NF was -0.32 ± 0.83 Tg C per year (gain) in 1990 and -0.85 ± 1.42 Tg C per year in 2012 (gain) (Fig. 3b). The uncertainty between annual estimates can make it difficult to determine whether the forest is a sink or a source in a specific year (i.e., uncertainty bounds overlap zero) (Fig. 3a and 3b). However, the trend of increasing carbon stocks from 1990 to 2013 (Fig. 1) over the 23-year period suggests that both the George Washington and Jefferson NF's are modest carbon sinks.

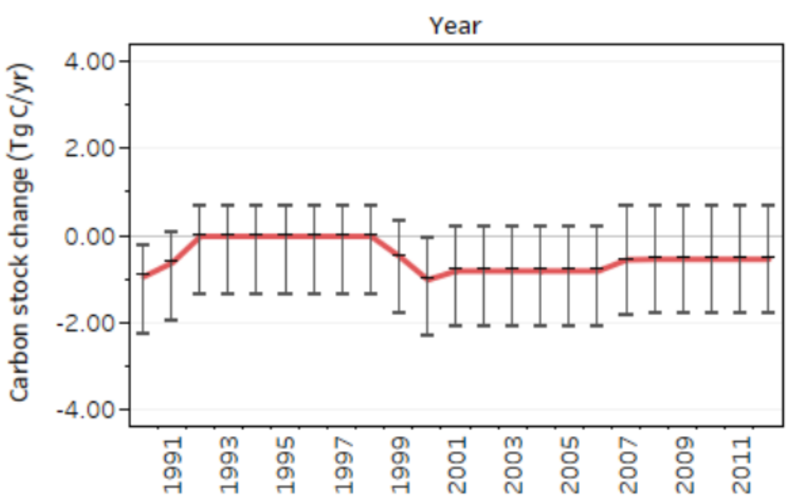
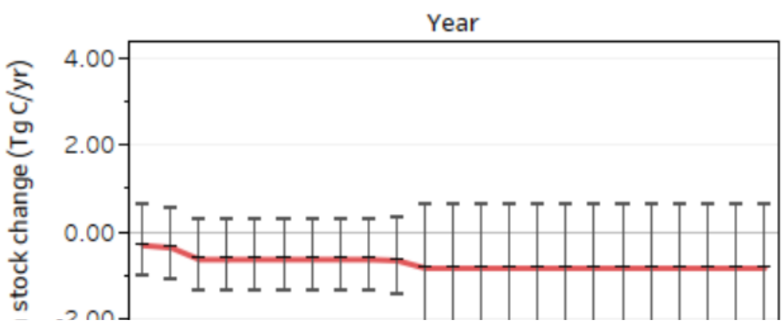


Figure 3a. *Carbon stock change (Tg/yr) from 1990 to 2012 for George Washington and Jefferson the George Washington National Forest, bounded by 95 percent confidence intervals. A positive value indicates a carbon source, and a negative value indicates a carbon sink. Estimated using the CCT model.*

Changes in forested area may affect whether forest carbon stocks are increasing or decreasing. The CCT estimates from the Baseline Report are based on FIA data, which may indicate changes in the total forested area from one year to the next. According to the FIA data used to develop these baseline estimates, the forested area in the George Washington NF has increased from 397,729 ha in 1990 to 446,362 ha in 2013, a net change of 48,633 ha.[2] The forested area in the Jefferson NF has increased from 255,009 ha in 1990 to 328,759 ha in 2013, a net change of 73,749 ha. When forestland area increases, total ecosystem carbon stocks typically also increase, indicating a carbon sink. The CCT model used inventory data from two different databases. This may have led to inaccurate estimates of changes in forested area, potentially altering the conclusion regarding whether or not forest carbon stocks are increasing or decreasing, and therefore, whether the National Forest is a carbon source or sink (Woodall *et al.*, 2011).

Carbon density, which is an estimate of forest carbon stocks per unit area, can help identify the effects of changing forested area. In the George Washington NF, carbon density increased from about 147 Megagrams of carbon (Mg C) per ha in 1990 to 157 Mg C per ha in 2013. For the Jefferson National Forest these numbers were 145 Mg C per ha and 164 Mg C per ha (Fig. 4a and 4b). These increases in carbon density suggests that total carbon stocks may have indeed increased.



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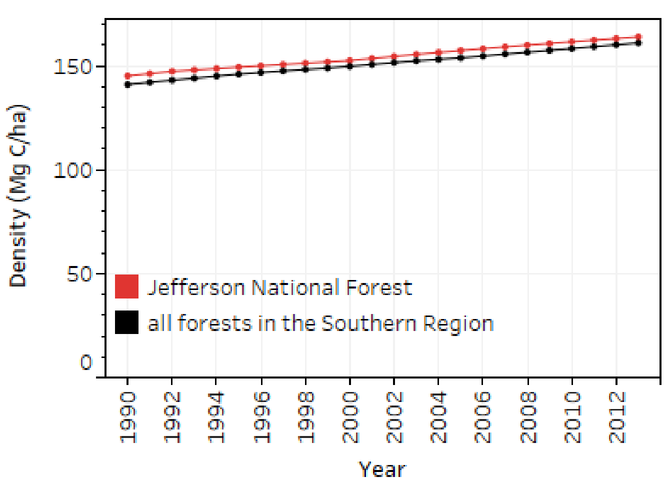

Figure 4b*. Carbon stock density (Megagrams per hectare) in the Jefferson National Forest and the average carbon stock density for all forests in the Southern Region from 1990 to 2013. Estimated using CCT.*

Carbon density is also useful for comparing trends among units or ownerships with different forest areas. Similar to the George Washington and Jefferson NF's, most national forests in the Southern Region have experienced increasing carbon densities from 1990 to 2013. Carbon density in the George Washington NF has been similar to but slightly lower than the average for all national forest units in the Southern Region (Fig.4a) while the Jefferson NF has been slightly higher than the Southern Region average (Fig. 4b). Differences in carbon density between units may be related to inherent differences in biophysical factors that influence growth and productivity, such as climatic conditions, elevation, and forest types. These differences may also

[2] Forested area used in the CCT model may differ from more recent FIA estimates, as well as from the forested areas used in the other modeling tools.

be affected by disturbance and management regimes (see Section 3.0).

2.2 Uncertainty associated with baseline forest carbon estimates

All results reported in this assessment are estimates that are contingent on models, data inputs, assumptions, and uncertainties. Baseline estimates of total carbon stocks and carbon stock change include 95 percent confidence intervals derived using Monte Carlo simulations[3] and shown by the error bars (Figs. 1, 3). These confidence intervals indicate that 19 times out of 20, the carbon stock or stock change for any given year will fall within error bounds. The uncertainties contained in the models, samples, and measurements can exceed 30 percent of the mean at the scale of a national forest, sometimes making it difficult to infuse if or how carbon stocks are changing.

The baseline estimates that rely on FIA data include uncertainty associated with sampling error (e.g., area estimates are based on a network of plots, not a census), measurement error (e.g., species identification, data entry errors), and model error (e.g., associated with volume, biomass, and carbon equations, interpolation between sampling designs). As mentioned in Section 2.1, one such model error has resulted from a change in FIA sampling design, which led to an apparent change in forested area. Change in forested area may reflect an actual change in land use due to reforestation or deforestation. However, given that the George Washington and Jefferson NF's have experienced minimal changes in land use or adjustments to the boundaries of the national forests in recent years, the change in forested area incorporated in CCT is more likely a data artefact of altered inventory design and protocols (Woodall *et al.*, 2013).

The inventory design changed from a periodic inventory, in which all plots were sampled in a single year to a standardized, national, annual inventory, in which a proportion of all plots is sampled every year. The older, periodic inventory was conducted differently across states and tended to focus on timberlands with high productivity. Any data gaps identified in the periodic surveys, which were conducted prior to the late 1990s, were filled by assigning average carbon densities calculated from the more complete, later inventories from the respective states (Woodall *et al.*, 2011). The definition of what constitutes forested land also changed between the periodic and annual inventory in some states, which may also have contributed to apparent changes in forested area.

In addition, carbon stock estimates contain sampling error associated with the cycle in which inventory plots are measured. Forest Inventory and Analysis plots are resampled about every 5 years in the eastern United States, and a full cycle is completed when every plot is measured at least once. However, sampling is designed such that partial inventory cycles provide usable, unbiased samples annually but with higher errors. These baseline estimates may lack some temporal sensitivity, because plots are not resampled every year, and recent disturbances may not be incorporated in the estimates if the disturbed plots have not yet been sampled. For example, if a plot was measured in 2009 but was clear-cut in 2010, that harvest would not be detected in that

[3] A Monte Carlo simulation performs an error analysis by building models of possible results by substituting a range of values – a probability distribution – for any factor that has inherent uncertainty (e.g., data inputs). It then calculates results over and over, each time using a different set of random values for the probability functions.

plot until it was resampled in 2014. Therefore, effects of the harvest would show up in FIA/CCT estimates only gradually as affected plots are re-visited and the differences in carbon stocks are interpolated between survey years (Woodall *et al.*, 2013). In the interim, re-growth and other disturbances may mute the responsiveness of CCT to disturbance effects on carbon stocks. Although CCT is linked to a designed sample that allows straightforward error analysis, it is best suited for detecting broader and long-term trends, rather than annual stock changes due to individual disturbance events.

In contrast, the Disturbance Report (Section 3.0) integrates high-resolution, remotely-sensed disturbance data to capture effects of each disturbance event the year it occurred. This report identifies mechanisms that alter carbon stocks and provides information on finer temporal scales. Consequently, discrepancies in results may occur between the Baseline Report and the Disturbance Report (Dugan *et al.*, 2017).

2.3 Carbon in Harvested Wood Products

Although harvest transfers carbon out of the forest ecosystem, most of that carbon is not lost or emitted directly to the atmosphere. Rather, it can be stored in wood products for a variable duration depending on the commodity produced. Wood products can be used in place of other more emission intensive materials, like steel or concrete, and wood-based energy can displace fossil fuel energy, resulting in a substitution effect (Gustavsson *et al.,* 2006; Lippke *et al.,* 2011). Much of the harvested carbon that is initially transferred out of the forest can also be recovered with time as the affected area regrows.

Carbon accounting for harvested wood products (HWP) contained in the Baseline Report was conducted by incorporating data on harvests on national forests documented in cut-and-sold reports within a production accounting system (Loeffler *et al.*, 2014). This approach tracks the entire cycle of carbon, from harvest to timber products to primary wood products to disposal. As more commodities are produced and remain in use, the amount of carbon stored in products increases. As more products are discarded, the carbon stored in solid waste disposal sites (landfills, dumps) increases. Products in solid waste disposal sites may continue to store carbon for many decades.

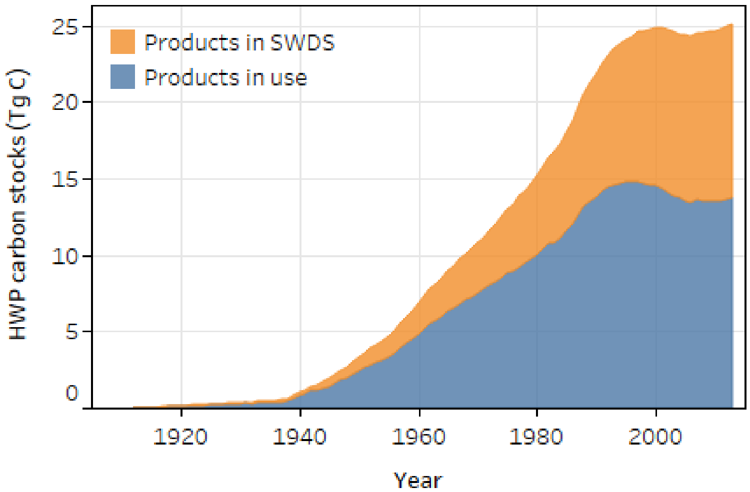

Figure 5*. Cumulative total carbon (Tg) stored in harvested wood products (HWP) sourced from national forests in the* Southern Region*. Carbon in HWP includes products that are still in use and carbon stored at solid waste disposal sites (SWDS). Estimated using the IPCC production accounting approach.*

In national forests in the Southern Region, harvest levels remained low until after the start of World War II in the late 1930s, when they began to increase, which caused an increase in carbon storage in HWP (Fig. 5). Timber harvesting and subsequent carbon storage later increased rapidly from the 1980s. Storage in products and landfills reached about 25 Tg C in 2001. However, because of a significant decline in harvesting in the late 1990's (to 1950s levels), carbon accumulation in the product sector has slowed, and carbon storage in products in use has declined since it peaked in the late 1990's. Despite this decline, the contribution of national forest timber harvests to the HWP carbon pool exceeds the decay of retired products, causing a net increase in product-sector carbon stocks in the Southern Region. In 2013, the carbon stored in HWP was equivalent to approximately 2.7 percent of total forest carbon storage associated with national forests in the Southern Region .

2.4 Uncertainty associated with estimates of carbon in harvested wood products

As with the baseline estimates of ecosystem carbon storage, the analysis of carbon storage in HWP also contains uncertainties. Sources of error that influence the amount of uncertainty in the estimates include: adjustment of historic harvests to modern national forest boundaries; factors used to convert the volume harvested to biomass; the proportion of harvested wood used for different commodities (e.g., paper products, saw logs); product decay rates; and the lack of distinction between methane and CO_2 emissions from landfills. The approach also does not consider the substitution of wood products for emission-intensive materials or the substitution of bioenergy for fossil fuel energy, which can be significant (Gustavsson *et al.*, 2006). The collective effect of uncertainty was assessed using a Monte Carlo approach. Results indicated a ±0.05 percent difference from the mean at the 90 percent confidence level for 2013, suggesting that uncertainty is relatively small at this regional scale (Loeffler *et al.*, 2014).

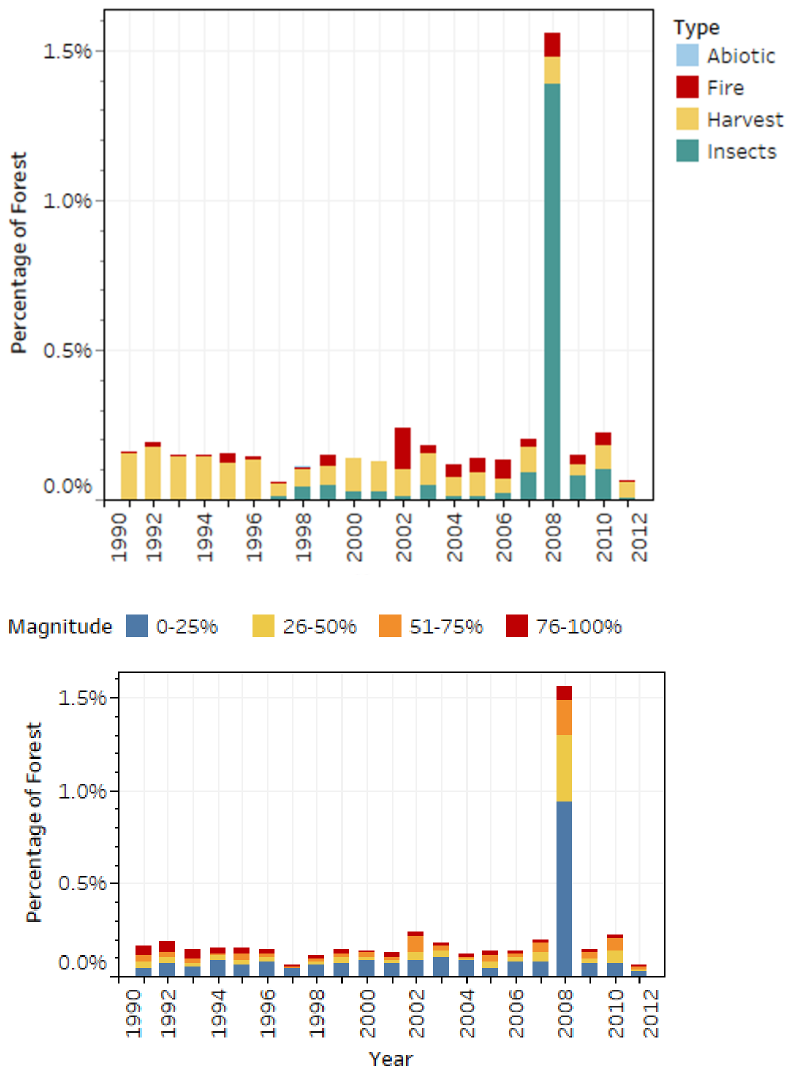

Figure 6a and 6b. *Percentage of forest disturbed from 1990 to 2011 in George Washington and Jefferson National Forest by (a) disturbance type including fire, harvests, insects, and abiotic (wind), and (b) magnitude of disturbance (change in canopy cover). Estimated using annual disturbance maps derived from Landsat satellite imagery.*

3.0 Factors Influencing Forest Carbon

3.1 Effects of Disturbance

The Disturbance Report builds on estimates in the Baseline Report by supplementing high-resolution, manually-verified, annual disturbance data from Landsat satellite imagery (Healey *et al.*, 2018). The Landsat imagery was used to detect land cover changes due to disturbances including fires, harvests, insects, and abiotic factors (e.g., wind, ice storms). The resulting disturbance maps indicate that timber harvest has been the dominant disturbance type detected on the George Washington and Jefferson NF's from 1990 to 2011, in terms of the total percentage of forested area disturbed over the period (Fig. 6a). However, according to the satellite imagery, timber harvests affected a relatively small area of the forest during this time. In most years, timber harvests affected less than 0.1 percent of the total forested area of the George Washington and Jefferson NF's in any single year from 1990 to 2011, and in total less than 2 percent (approximately 14,050 ha) of the average forested area during this period (703,141 ha). The percentage of the forest harvested annually has also decreased slightly over this 21-year period. Although harvests varied in proportion of trees removed, they generally removed less than 25 percent of canopy cover (magnitude) (Fig. 6b). Although harvest was the dominant disturbance, there were some years where fire and insect and disease disturbances were greater. In total insect and disease accounted for 1.92% of the land base of the total forest disturbance from 1990 to 2001. 2008 was an outlier year with a heavy gypsy moth impact that specific year.

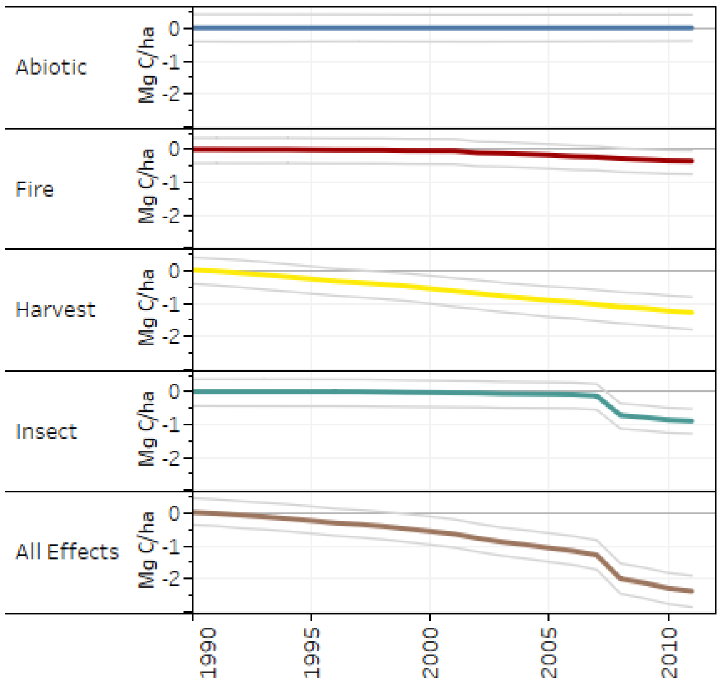

Figure 7. Lost potential storage of carbon (Megagrams) as a result of disturbance for the period 1990-2011 in the George Washington and Jefferson National Forests. The zero line represents a hypothetical undisturbed scenario. Gray lines indicate 95% confidence intervals. Estimated using the ForCaMF model.

The Forest Carbon Management Framework (ForCaMF) incorporates Landsat disturbance maps summarized in Figure 6, along with FIA data in the Forest Vegetation Simulator (FVS) (Crookston & Dixon, 2005). The FVS is used to develop regionally representative carbon accumulation functions for each combination of forest type, initial carbon density, and disturbance type and severity (including undisturbed) (Raymond *et al.*, 2015). The ForCaMF model then compares the undisturbed scenario with the carbon dynamics associated with the historical disturbances to estimate how much more carbon would be on each national forest if the disturbances and harvests during 1990-2011 had not occurred. ForCaMF simulates the effects of disturbance and management only on non-soil carbon stocks (i.e., vegetation, dead wood, forest floor). Like CCT, ForCaMF results supply 95 percent confidence intervals around estimates derived from a Monte Carlo approach (Healey *et al.*, 2014).

Timber harvesting on the George Washington and Jefferson NF's was the primary disturbance influencing carbon stocks from 1990 to 2011 (Fig. 7). Harvesting accounted for nearly 54 percent of the total non-soil carbon lost from the forest due to disturbances (USDA Forest Service, 2015). The ForCaMF model indicates that, by 2011, George Washington and Jefferson NF's contained 1.27 Mg C per ha less non-soil carbon (i.e., vegetation and associated pools) due to harvests since 1990, as compared to a hypothetical undisturbed scenario (Fig. 7). As a result, non-soil carbon stocks in the George Washington and Jefferson NF's would have been approximately 1 percent higher in 2011 if harvests had not occurred since 1990 (Fig. 8).

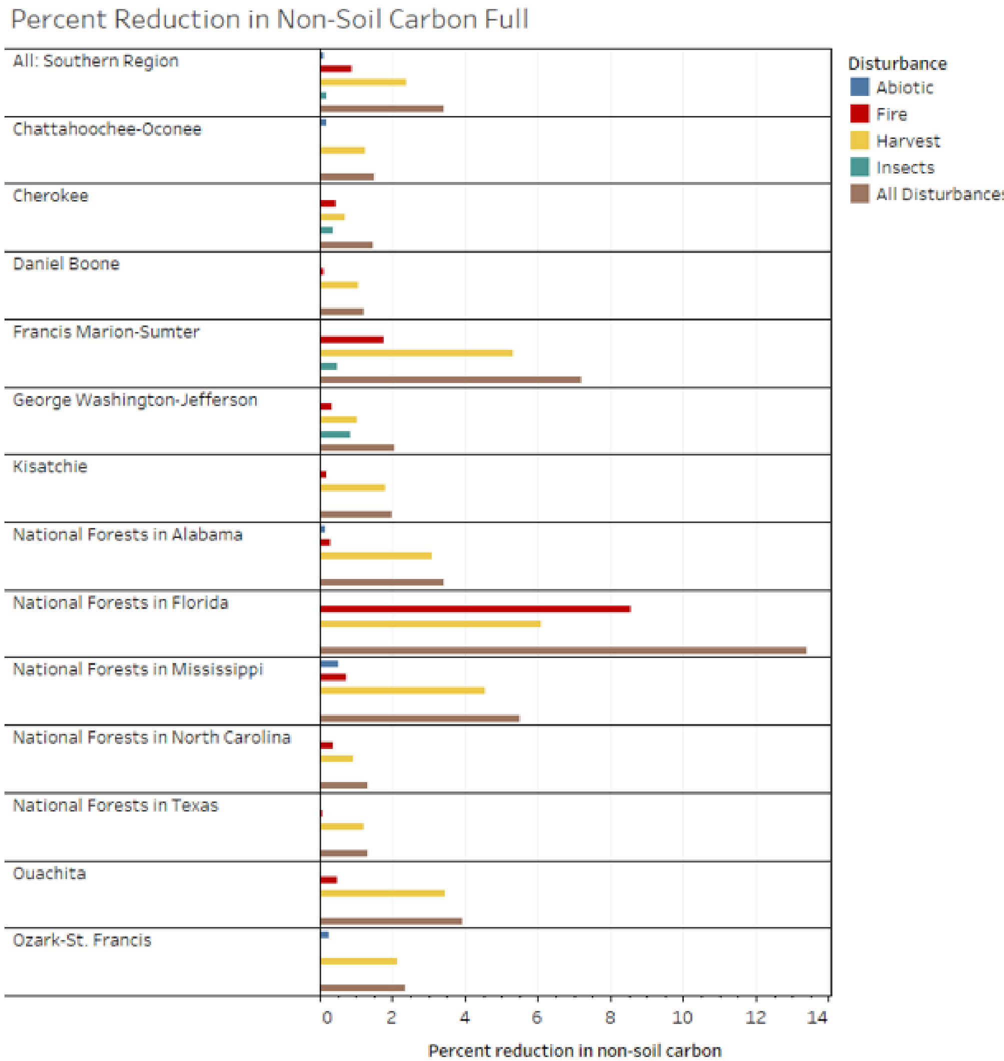

Figure 8. *The degrees to which 2011 carbon storage on each national forest in the Southern Region was reduced by disturbance from 1990 to 2011 relative to a hypothetical baseline with no disturbance. The black line indicates the effect of all disturbances types combined.*

Across all national forests in the Southern Region harvest has been the most significant disturbance affecting carbon storage since 1990, causing non-soil forest ecosystem carbon stocks to be 2.4 percent lower by 2011 (Fig. 8). Considering all national forests in the Southern Region, by 2011, fire accounted for the loss of 1 percent of non-soil carbon stocks, insects 0.2 percent, and abiotic factors (wind, ice storms) only 0.1 percent.

The ForCaMF analysis was conducted over a relatively short time. After a forest is harvested, it will eventually regrow and recover the carbon removed from the ecosystem in the harvest. However, several decades may be needed to recover the carbon removed depending on the type of the harvest (e.g., clear-cut versus partial cut), as well as the conditions prior the harvest (e.g., forest type and amount of carbon) (Raymond *et al.*, 2015). The ForCaMF model also does not track carbon stored in harvested wood after it leaves the forest ecosystem. In some cases, removing carbon from forests for human use can result in lower net contributions of GHGs to the atmosphere than if the forest was not managed, when accounting for the carbon stored in wood products, substitution effects, and forest regrowth (Lippke *et al.*, 2011; McKinley *et al.*, 2011; Skog *et al.*, 2014; Dugan *et al.*, 2018). Therefore, the IPCC recognizes wood as a renewable resource that can provide a mitigation benefit to climate change (IPCC, 2000).

ForCaMF helps to identify the biggest local influences on continued carbon storage and puts the recent effects of those influences into perspective. Factors such as stand age, drought, and climate may affect overall carbon change in ways that are independent of disturbance trends. The purpose of the InTEC model was to reconcile recent disturbance impacts with these other factors.

3.2 Effects of Forest Aging

InTEC models the collective effects of forest disturbances and management, aging, mortality, and subsequent regrowth on carbon stocks from 1950 to 2011. The model uses inventory-derived maps of stand age, Landsat-derived disturbance maps (Fig. 6), and equations describing the relationship between net primary productivity (NPP) and stand age. Stand age serves as a proxy for past disturbances and management activities (Pan *et al.*, 2011a). In the model, when a forested stand is disturbed by a severe, stand-replacing event, the age of the stand resets to zero and the forest begins to regrow. Thus, peaks of stand establishment can indicate stand-replacing disturbance events that subsequently promoted regeneration.

Stand-age distribution for the George Washington and Jefferson NF's derived from 2011 forest inventory data indicates elevated stand establishment around 1900-1920 (Fig. 9a). This period of elevated stand regeneration came after decades of intensive logging and large wildfires in the late 1800s and early 1900s (Foster, 2006). Policies focusing on restoring forests after decades of overharvesting and conversion of forest to agriculture enabled these stands to establish, survive, and accumulate carbon. Similar age trends have been widely observed in eastern U.S. forests (Birdsey *et al.*, 2006). Stands regrow and recover at different rates depending on forest type and site conditions. Forests are generally most productive when they are young to middle age, then productivity peaks and declines or stabilizes as the forest canopy closes and as the stand experiences increased respiration and mortality of older trees (Pregitzer & Euskirchen, 2004; He *et al.*, 2012), as indicated by the in NPP-age curves (Fig. 9b), derived in part from FIA data.

InTEC model results show that George Washington and Jefferson NF's were accumulating carbon steadily at the start of the analysis in the 1950s through the mid-1970s (Fig. 10) (positive slope) as a result of regrowth following disturbances and heightened productivity of the young to middle-aged forests (30-60 years old) (Fig. 9b). As stand establishment declined and more stands reached slower growth stages around the 1970s, the rate of carbon accumulation declined (negative slope). While forest regrowth and aging following historical disturbances (early 1900s harvesting and land-use change), have collectively played an important role in carbon accumulation trends since 1950 in the George Washington and Jefferson NF's (Fig. 10), the effects of non-disturbance factors have become more important in influencing carbon trends on the forest.

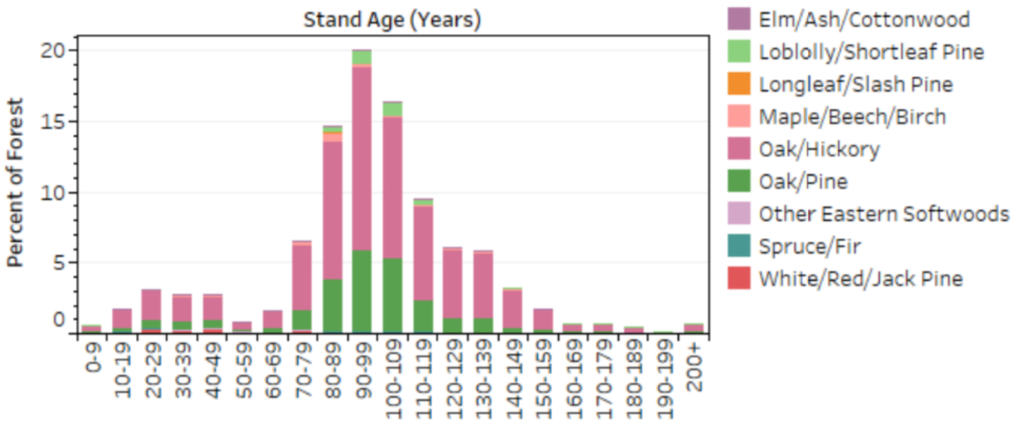

Figure 9. *(a) Stand age distribution in 2011 by forest type group in the George Washington and Jefferson National Forests. Derived from forest inventory data.*

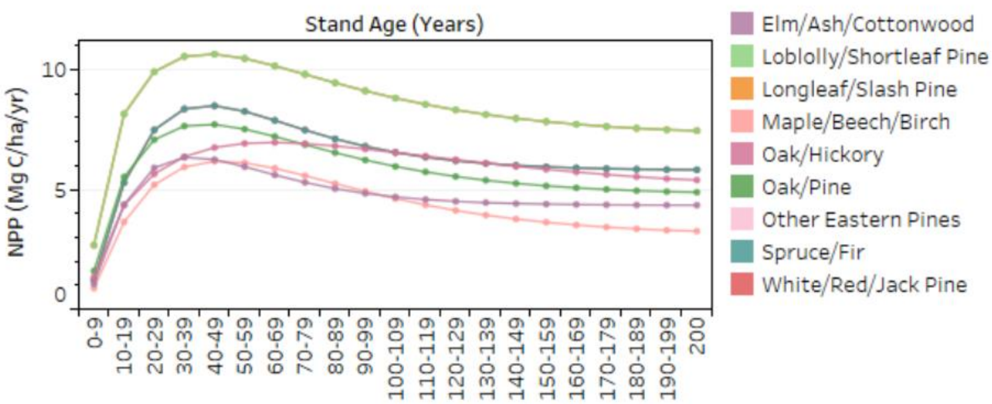

Figure 9. *(b) net primary productivity-stand age curves by forest type group in the George Washington and Jefferson National Forests. Derived from forest inventory data and He et al. 2012.*

3.3 Effects of Climate and Environment

The InTEC model also isolates the effects of climate (temperature and precipitation), atmospheric CO_2 concentrations, and nitrogen deposition on forest carbon stock change and accumulation. Generally annual precipitation and temperature conditions fluctuate considerably. The modeled effects of variability in temperature and precipitation on carbon stocks has varied from year-to-year, but overall, climate since 1950 has had a small positive effect on carbon stocks in the George Washington and Jefferson National Forests (Fig. 10). Warmer temperatures can increase forest carbon emissions through enhanced soil microbial activity and higher respiration (Ju *et al.*, 2007; Melillo *et al.*, 2017), but warming temperatures can also reduce soil moisture through increased evapotranspiration, causing lower forest growth (Xu *et al.*, 2013).

In addition to climate, the availability of CO_2 and nitrogen can alter forest growth rates and subsequent carbon uptake and accumulation (Caspersen *et al.*, 2000; Pan *et al.*, 2009). Increased fossil fuel combustion, expansion of agriculture, and urbanization have caused a significant increase in both CO_2 and nitrogen emissions (Chen *et al.*, 2000; Keeling *et al.*, 2009; Zhang *et al.*, 2012). According to the InTEC model, higher CO_2 has consistently had a positive effect on carbon stocks in George Washington and Jefferson NF's, tracking an increase in atmospheric CO_2 concentrations worldwide (Fig. 10). However, a precise quantification of the magnitude of this CO_2 effect on terrestrial carbon storage is one of the more uncertain factors in ecosystem modeling (Jones *et al.*, 2014; Zhang *et al.*, 2015). Long-term studies examining increased atmospheric CO_2 show that forests initially respond with higher productivity and growth, but the effect is greatly diminished or lost within 5 years in most forests (Zhu *et al.*, 2016). There has been considerable debate regarding the effects of elevated CO_2 on forest growth and biomass accumulation, thus warranting additional study (Körner *et al.*, 2005; Norby *et al.*, 2010; Zhu *et al.*, 2016).

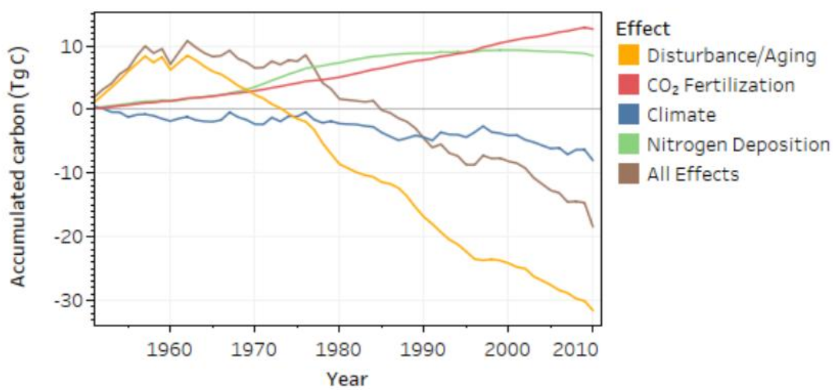

Figure 10. *Accumulated carbon in the George Washington and Jefferson National Forests due to disturbance/aging, climate, nitrogen deposition, CO_2 fertilization, and all factors combined (shown in black line) for1950–2011, excluding carbon accumulated pre-1950 Estimated using the InTEC model.*

Modeled estimates suggest that overall nitrogen deposition had a positive effect on carbon accumulation in the George Washington and Jefferson NF's (Fig. 10). Like CO_2, the actual magnitude of this effect remains uncertain. Estimates from inventory data in the northeast and north-central United States confirm that nitrogen deposition has enhanced growth among most tree species, subsequently increasing forest carbon accumulation (Thomas *et al.*, 2010). However, elevated nitrogen deposition can also decrease growth in some species for a variety of reasons, such as leaching of base cations in the soil, increased vulnerability to secondary stressors, and suppression by more competitive species (Pardo *et al.*, 2011). Some regional studies have documented negative effects on forest productivity associated with chronically high levels of nitrogen deposition in the eastern United States (Boggs *et al.*, 2005; Pardo *et al.*, 2011). The InTEC model simulated that rates of carbon accumulation associated with nitrogen deposition decreased as deposition rates declined. Overall, the InTEC model suggests that CO_2 and nitrogen fertilization partially offset the declines in carbon accumulation associated with historical disturbance, aging, and regrowth, and climate.

3.4 Uncertainty associated with disturbance effects and environmental factors

As with the baseline estimates, there is also uncertainty associated with estimates of the relative effects of disturbances, aging, and environmental factors on forest carbon trends. For example, omission, commission, and attribution errors may exist in the remotely-sensed disturbance maps used in the ForCaMF and InTEC models. However, these errors are not expected to be significant given that the maps were manually verified, rather than solely derived from automated methods. ForCaMF results may also incorporate errors from the inventory data and the FVS-derived carbon accumulation functions (Raymond *et al.*, 2015). To quantify uncertainties, the ForCaMF model employed a Monte Carlo-based approach to supply 95 percent confidence intervals around estimates (Healey *et al.*, 2014).

Uncertainty analyses such as the Monte Carlo are not commonly conducted for spatially explicit, process-based models like InTEC because of significant computational requirements. However, process-based models are known to have considerable uncertainty, particularly in the parameter values used to represent complex ecosystem processes (Zaehle *et al.*, 2005). InTEC is highly calibrated to FIA data and remotely-sensed observations of disturbance and productivity, so uncertainties in these datasets are also propagated into the InTEC estimates. National-scale sensitivity analyses of InTEC inputs and assumptions (Schimel *et al.*, 2015), as well as calibration with observational datasets (Zhang *et al.*, 2012) suggest that model results produce a reasonable range of estimates of the total effect (e.g., Fig. 10, "All effects"). However, the relative partitioning of the effects of disturbance and non-disturbance factors as well as uncertainties at finer scales (e.g., national forest scale) are likely to be considerably higher.

Results from the ForCaMF and InTEC models may differ substantially from baseline estimates (CCT), given the application of different datasets, modeling approaches, and parameters (Zhang *et al.*, 2012; Dugan *et al.,* 2017). The baseline estimates are almost entirely rooted in empirical forest inventory data, whereas ForCaMF and InTEC involve additional data inputs and modeling complexity beyond summarizing ground data.

4.0 Future Carbon Conditions

4.1 Prospective Forest Aging Effects

The retrospective analyses presented in the previous sections can provide an important basis for understanding how various factors may influence carbon storage in the future. For instance, the forests of the George Washington and Jefferson NF's are mostly middle-aged and older (greater than 80 years) and few stands are young (Fig. 9a). If the Forest continues on this aging trajectory, more stands will reach a slower growth stage in coming years and decades (Fig. 9b), potentially causing the rate carbon accumulation to decline and the Forest may eventually transition to a steady state in the future. Although yield curves indicate that biomass carbon stocks may be approaching maximum levels (Fig. 9b), ecosystem carbon stocks can continue to increase for many decades as dead organic matter and soil carbon stocks continue to accumulate (Luyssaert *et al.*, 2008). Furthermore, while past and present aging trends can inform future conditions, the applicability may be limited, because potential changes in management activities or disturbances could affect future stand age and forest growth rates (Davis *et al.*, 2009; Keyser & Zarnoch, 2012).

The RPA assessment provides regional projections of forest carbon trends across forestland ownerships in the United States based on a new approach that uses the annual inventory to estimate carbon stocks retrospectively to 1990 and forward to 2060 (Woodall *et al.*, 2015; USDA Forest Service, 2016). The RPA reference scenario assumes forest area in the U.S. will continue to expand at current rates until 2022, when it will begin to decline due to land use change. However, national forests tend to have higher carbon densities than private lands and may have land management objectives and practices that differ from those on other lands.

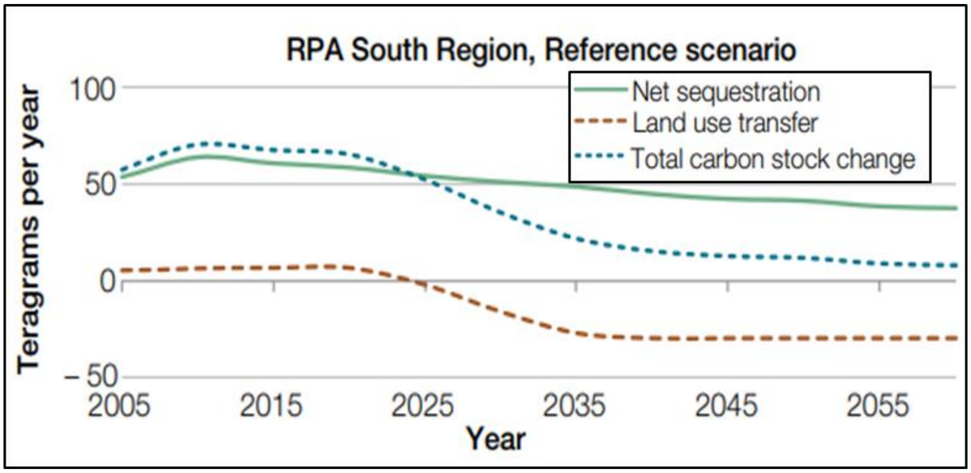

Figure 11. *Projections of forest carbon stock changes in the South Region (equivalent to the boundaries of Southern Region, but includes all land tenures) for the RPA reference scenario. Net sequestration of forests is the total carbon stock change minus losses associated with land-use change.*

For RPA's South Region (equivalent to Forest Service's Southern Region boundary, but includes all land ownerships), projections indicate that the rate of carbon sequestration began to decline since approximately 2010 and will continue to decline through 2060, but at a slower rate in the middle of the century. This decline in the carbon sink is mostly due to the loss of forestland (land-use transfer), and to a lesser extent through forest aging and increased disturbances (net sequestration) (Fig. 11). At the global and national scales, changes in land use—especially the conversion of forests to non-forest land (deforestation)—have a substantial effect on carbon stocks (Pan *et al.*, 2011b; Houghton *et al.*, 2012). Converting forest land to a non-forest use removes a large amount of carbon from the forest and inhibits future carbon sequestration. National forests tend to experience low rates of land-use change, and thus, forest land area is not expected to change substantially within the George Washington and Jefferson NF's in the future. Therefore, on national forest lands, the projected carbon trends may closely resemble the "net sequestration" trend in Fig. 11, which isolates the effects of forest aging, disturbance, mortality, and growth from land-use transfers and indicates a small decline in the rate of net carbon sequestration through 2060.

4.2 Prospective Climate and Environmental Effects

The observational evidence described above and in previous sections highlights the role of natural forest development and succession as the major driver of historic and current forest carbon sequestration that is occurring at the George Washington and Jefferson NF's and elsewhere in across the region. Several other modeling studies that have been conducted across the Eastern region simulate future changes in forest growth, biomass, and carbon through the middle or end of the 21st century (Ollinger *et al.*, 2008; Thompson *et al.*, 2011; Tang *et al.*, 2014). Although these studies may include multiple ownerships and vary in the degree that they incorporate the potential for carbon changes from forest harvest and natural disturbances, they all include scenarios of climate change. From this collection of work, the collective evidence points to continued forest growth and recovery from past disturbances as the major driver of landscape-scale forest carbon gains for many decades into the future, in the absence of major disturbances from climate change or other causes (Shifley & Moser, 2016; Janowiak *et al.*, 2018).

Climate change introduces additional uncertainty about how forests—and forest carbon sequestration and storage—may change in the future. Climate change causes many direct alterations of the local environment, such as changes in temperature and precipitation, and it has indirect effects on a wide range of ecosystem processes (Vose *et al.*, 2012). Further, disturbance rates are projected to increase with climate change (Vose *et al.*, 2018) making it challenging to use past trends to project the effects of disturbance and aging on forest carbon dynamics.

A climate change vulnerability assessment of the southeast (McNulty et al., 2018), which encompasses the George Washington and Jefferson NF's, indicates annual mean temperature increases across the Southeast for all future time periods and emission scenarios. Model simulations also predict an increase in the number of hot days (maximum temperatures of more than 95°F) and an increase in the length of the freeze-free season ranging from 20 to 30 days by mid-century. The number of days with daytime temperatures above 95°F is expected to increase across the region, with extreme increases in the southern part of the region by as much as 50 days per year, and summer temperatures increasing substantially.

Average annual precipitation in the Southeast is projected to increase with the greatest increases occurring in the winter. The number of wet days (precipitation exceeding 1 inch) is projected to increase throughout the Southeast, particularly across the Appalachian mountains (Kunkel et al., 2013). Drought, wildfires, insect and plant invasions, and more intense storms all pose threats to the health and resiliency of southeastern forests. Scientists expect that increases in temperature and changes in rainfall patterns will cause these disturbances to become more common and with greater intensity and duration (McNulty et al., 2013).

Elevated temperatures may increase soil respiration and reduce soil moisture through increased evapotranspiration, which would negatively affect growth rates and carbon accumulation (Ju et al., 2007; Melillo et al., 2017). Modeled results of recent climate effects using the InTEC model indicate that years with elevated temperatures have generally had a negative effect on carbon uptake in the George Washington and Jefferson NF's (Fig. 10).

Changes in climate are expected to drive many other changes in forests through the next century, including changes in forest establishment and composition (McNulty *et al.*, 2015). Changing temperature and rainfall patterns may threaten the survival of northern hardwood trees in mountain forests. Higher temperatures will allow species from lower elevations to migrate up-slope into higher areas, thereby changing the species mix of current forest communities. Hardwood forests may also experience stress from higher temperatures, allowing pines and other fast-growing species to become more dominant at the expense of slower-growing species such as hickories and oaks. Forest landowners should observe the responses of these species to any stress caused by drought and higher temperatures and may need to thin tree densities to increase water availability for remaining trees or, ultimately, shift management focus away from northern hardwood species. Spruce-fir forests are also at high risk.

Carbon dioxide emissions are projected to increase through 2100 under even the most conservative emission scenarios (IPCC, 2014). Several models, including the InTEC model (Figure 10), project greater increases in forest productivity when the CO_2 fertilization effect is included in modeling (Aber *et al.*, 1995; Ollinger *et al.*, 2008; Pan *et al.*, 2009; Zhang *et al.*, 2012). However, the effect of increasing levels of atmospheric CO_2 on forest productivity is transient and can be limited by the availability of nitrogen and other nutrients (Norby *et al.*, 2010). Productivity increases under elevated CO2 could be offset by losses from climate-related stress or disturbance.

Given the complex interactions among forest ecosystem processes, disturbance regimes, climate, and nutrients, it is difficult to project how forests and carbon trends will respond to novel future conditions. The effects of future conditions on forest carbon dynamics may change over time. As climate change persists for several decades, critical thresholds may be exceeded, causing unanticipated responses to some variables like increasing temperature and CO2 concentrations. The effects of changing conditions will almost certainly vary by species and forest type. Some factors may enhance forest growth and carbon uptake, whereas others may hinder the ability of forests to act as a carbon sink, potentially causing various influences to offset each other. Thus, it will be important for forest managers to continue to monitor forest responses to these changes and potentially alter management activities to better enable forests to better adapt to future conditions.

5.0 Summary

Forests in the George Washington and Jefferson NF's are maintaining a carbon sink. Forest carbon stocks increased by about 30 percent between 1990 and 2013, and negative impacts on carbon stocks caused by disturbances and environmental conditions have been modest and exceeded by forest growth. According to satellite imagery, timber harvesting has been the most prevalent disturbance detected on the Forest since 1990. However, harvests during this period have been relatively small and low intensity. Forest carbon losses associated with harvests have been small compared to the total amount of carbon stored in the Forest, resulting in a loss of about 1 percent of non-soil carbon from 1990 to 2011. These estimates represent an upper bound because they do not account for continued storage of harvested carbon in wood products or the effect of substitution. Carbon storage in HWPs sourced from national forests increased since the early 1900s. Recent declines in timber harvesting have slowed the rate of carbon accumulation in the product sector.

The biggest influence on current carbon dynamics on the George Washington and Jefferson NF's is the legacy of intensive timber harvesting and land clearing for agriculture during the 19th century, followed by a period of forest recovery and more sustainable forest management beginning in the early to mid-20th century, which continues to promote a carbon sink today (Birdsey *et al.*, 2006). However, stands on the George Washington and Jefferson NF's are now mostly middle to older aged. The rate of carbon uptake and sequestration generally decline as forests age. Accordingly, projections from the RPA assessment indicate a potential age-related decline in forest carbon stocks in the Southern Region (all land ownerships) beginning in the 2020s.

Climate and environmental factors, including elevated atmospheric CO_2 and nitrogen deposition, have also influenced carbon accumulation on the George Washington and Jefferson NF's. Recent warmer temperatures and precipitation variability may have stressed forests, causing climate to have a negative impact on carbon accumulation in the 2000s. Conversely, increased atmospheric CO_2 and nitrogen deposition may have enhanced growth rates and helped to counteract ecosystem carbon losses due to historical disturbances, aging, and climate.

The effects of future climate conditions are complex and remain uncertain. However, under changing climate and environmental conditions, forests of the George Washington and Jefferson NF's may be increasingly vulnerable to a variety of stressors. These potentially negative effects might be balanced somewhat by the positive effects of longer growing season, greater precipitation, and elevated atmospheric CO_2 concentrations. However, it is difficult to judge how these factors and their interactions will affect future carbon dynamics on the George Washington and Jefferson NF's.

Forested area on the George Washington and Jefferson NF's will be maintained as forest in the foreseeable future, which will allow for a continuation of carbon uptake and storage over the long term. Across the broader region, land conversion for development on private ownerships is a concern (Shifley & Moser, 2016) and this activity can cause substantial carbon losses (FAOSTAT, 2013; USDA Forest Service, 2016). The George Washington and Jefferson NF's will continue to have an important role in maintaining the carbon sink, regionally and nationally, for decades to come.

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